MINIMIZING *1/f* NOISE IN MAGNETIC SENSORS WITH A MEMS FLUX CONCENTRATOR

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ABSTRACT

New approaches offer the promise of providing energy efficient, low cost, small, and highly sensitive magnetic sensors. However, the *1/f* noise of these new types of sensors is a major obstacle. Many army applications, such as detecting moving targets, require sensitivity as low frequencies. This paper reports development of a device, the MEMS flux concentrator, invented at ARL, that minimizes the effect of *1/f* noise in sensors. The device accomplishes this by shifting the operating frequency to higher frequencies where *1/f* noise is much lower. This shift is accomplished by modulating the magnetic field before it reaches the sensor. In our device, the magnetic sensor, a GMR sensor, is placed between flux concentrators that have been deposited on MEMS flaps. The motion of the MEMS flaps modulates the field by a factor of 3 at frequencies from 8 to 15 kHz. The MEMS flux concentrator should increase the sensitivity of many magnetic sensors by two to three orders of magnitude. An equally important benefit is that, because it is a modulation technique, it eliminates the problem of dealing with the large DC bias of most magnetoresistive sensors.

1. INTRODUCTION

To maximize their contribution to army programs such as Objective Force Warrior, and the Objective Force sensors should be energy efficient, low cost, small, and highly sensitive. Magnetic sensors are likely to be part of the suite of sensors that will be used in these programs. Magnetic sensors are passive sensors with desirable attributes for Army applications that include insensitivity to weather conditions, the requirement of only a small amount of band width, and the unique ability to "see through" walls and foliage without attenuation. Magnetic sensors can compliment other sensors such as acoustic sensors. Though acoustic sensors have a greater detection range they require considerable bandwidth, are sensitive to weather conditions, and can not "see through" walls. Another advantage of magnetic sensors is that it is nearly impossible to make a weapon or vehicle that does not include ferrous material that can be detected by magnetic sensors. Though the permanent magnetic moment of the ferrous material can be minimized by "deperming", the distortion of the earth's field due to the magnetic permeability is difficult to hide. Data from magnetic sensors can be fused with the data from other sensor modalities, such as acoustic and seismic sensors, to characterize or identify and track targets. Specifically, magnetic sensors can be used for perimeter defense, at check points, as part of a suite of sensors in unattended ground sensor networks, and on UGVs, and UAVs. They also can be employed to monitor rooms and passageways that have been cleared by troops.

The magnetic signals from military targets come from the internal motion of ferromagnetic parts and the motion of targets relative to the magnetic sensor. Both of these magnetic signals occur at low frequencies, typically less than 100 Hz. It should be noted that at low frequencies the magnetic and electric field amplitudes are not coupled as they are at radio frequencies. Thus, additional information can be obtained by using both electric and magnetic field sensors. Because the earth's field is usually larger than the field generated by the target, it is difficult to detect magnetic targets without having the field change by relative motion between the target and the sensor. The magnetic signal from targets at distance greater than the target size is usually like that of a magnet dipole and decreases as $1/r^3$ where r is the separation between the sensor and the target. The relatively short detection range of magnetic sensors is a consequence of this $1/r^3$ decrease of the signal. Because of the short range of magnetic sen-ors, a large number of low cost magnetic sensors must be used if one wants to guarantee detection over a large area.

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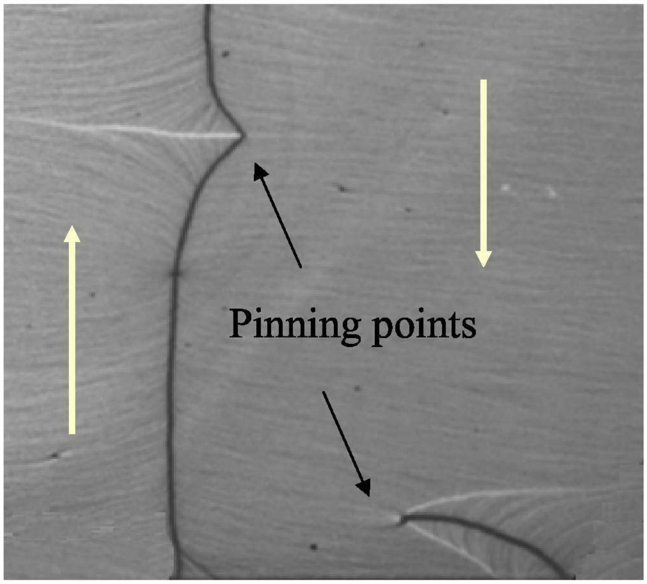


Figure 1. Transmission electron image of domain wall pinning. Image supplied by John Chapman, University of Glasgow. The vertical arrows indicate the direction of the magnetization.

To produce low cost sensors it probably necessary to use batch processing. There are several types of magnetoresistance sensors that can be produced by batch processing. The resistance of a magnetoresistance sensor is sensitive to the magnitude and direction of the magnetic field. The earliest type of magnetoresistance sensor was the anisotropic magnetoresistance sensor (AMR) [1], but new types of magnetoresistance sensors have been invented that have larger changes in resistance in response to an applied field. These new types of magnetoresistance sensor include giant (GMR) [2], and extraordinary magnetoresistance [3] sensors and spin dependent tunneling (SDT) [4] sensors. However, the *1/f* noise of these new types of sensors is a major obstacle in these sensors reaching their full potential.

To detect the relative motion between the target and the magnetic sensor requires high sensitivity in the frequency range f <1 Hz. Unfortunately, nearly all magnetoresistance sensors suffer from *1/f* noise. Further, there is a tendency [5] for the sensors that have a larger response to magnetic fields to also have more *1/f* noise. The *1/f* noise arises from domain wall motion and the interaction of domains. Figure 1 shows an illustrates the pinning of ferromagnetic domains. When a sufficiently large magnetic field is applied, the magnetic forces overcome the pinning forces and the domain wall abruptly moves. The excess energy is releases as noise. Thus, *1/f* noise is a serious problem in applying magnetic sensors to military applications. Figure 2 illustrates the *1/f* noise in spin dependent tunneling sensors. This paper discusses a device, the MEMS flux concentrator, which will greatly diminish the problem of *1/f* noise in small magnetic sensors. Figure 3 summarizes the problem and our solution.

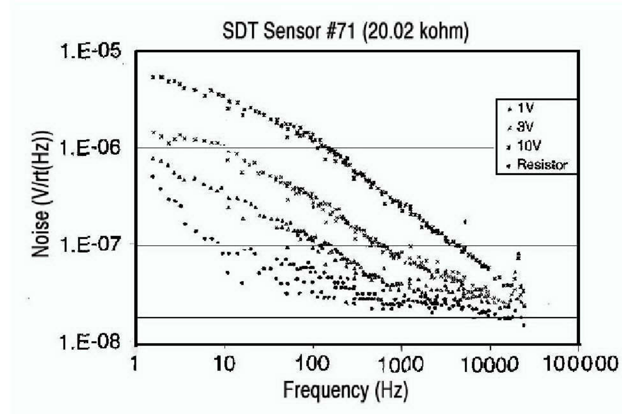


Figure 2. Example of 1/f noise in a spin dependent tunneling sensor.

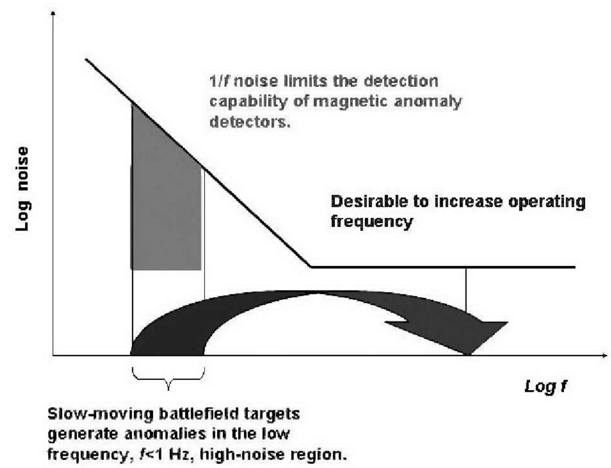


Figure 3 Illustration of the problem of 1/f noise in army applications and the advantage of shifting the operating frequency.

Another problem in using magneresistive sensors at low frequencies and at low fields is the fact that the field induced percentage change in the resistance is small. Thus, with a single device one must accurately measure a small change in a large signal. Because of this problem, most magnetoresistive sensors have bridge circuits to eliminate the DC offset. Using bridge circuits adds to the cost, complexity, and power consumption. For example, one must incorporate temperature compensation of the bridge elements in the design. This paper describes a device invented at ARL that mitigates the problems of 1/f noise in sensors and eliminates the DC offset.

2. CONCEPT

The MEMS flux concentrator[6] mitigates the effect of *1/f* noise in magnetic sensors by making a major modification in the standard design of magnetic sensors. Often in magnetic sensors the sense element is placed between a pair of flux concentrators. Flux concentrators are made of soft ferromagnetic materials, such as permalloy, and have the effect of enhancing the magnetic field at the position of the sensor by a factor of about 10. In our device, the flux concentrators are films deposited on microelectromechanical system (MEMS) [7] flaps. We are able to apply a voltage that drives the flaps to move and this changes the amount the magnetic field is enhanced at the position of the sensor. By driving the motion at kHz frequencies, we modulate the signal seen by the sensor to change at kHz frequencies. Thus, the sensor is operating at frequencies where, as seen in Fig. 2, the *1/f* noise can be as much as two or three orders of magnitude smaller. The original low frequency signal changes the amplitude of the higher frequency signal generated by the motion of the flux concentrators.

3. DESIGN

Designing the device required designing the flux concentrator and the MEMS structure and choosing the magnetic sensor and the electronics for processing the data.

3.1 Magnetic Sensor

We chose to use a spin valve as the magnetic sensor because spin valves are a relatively mature technology and, thus, are not be too difficult to fabricate. Spin valves [2] are a form of giant magnetoresistance sensors consisting of 4 thin films in a layered structure. A thin conducting layer is sandwiched between two ferromagnetic layers, one a soft ferromagnet and the other a pinned ferromagnet. An antiferromagnetic film is used to pin the magnetization of the ferromagnet. The exchange interactions at the interface between the ferromagnetic layer and the antiferromagnetic layer couple the two layers and make it more difficult to rotate the magnetization of the coupled ferromagnetic layer. The resistance of the structure is about 10% higher when the magnetization of the soft ferromagnet is antiparallel to the magnetization of the pinned ferromagnetic layer than when it is parallel to it. Unlike some magnetoresistance sensors, spin valves do not require a magnetic field to bias them into a linear, high sensitive region. The linear response is obtained by using shape anisotropy and proper annealing. Further, spin valves have considerable *1/f* noise and an improvement in their performance should be easily seen. The response for the device is often quoted as the change in output voltage per input voltage per Oe. The response for the spin valves used in our device is 7 mV/V/Oe. Starting with a silicon nitride coated silicon wafer substrate, the stack of materials deposited for the spin valve was the following: Ta/NiFeCo/Ta/NiFeCo/CoFe/Cu/CoFe/CrPtMn. The CrPtMn is the antiferromagnet used for pinning.

3.2 Flux Concentrator

Magnetic modeling was done using the finite element code Maxwell from Ansoft. This modeling was used to choose the separation between the flux concentrators, the thickness of the films, and how much motion was required to obtain an adequate modulation. Based on the modeling, it was estimated that ¼ micron thick permalloy flux concentrators separated 45 microns oscillating with a 12 micron amplitude would provide an enhancement of the magnetic field that varies between 6 at the smallest separation and 2 at the largest separation (See Fig. 2). The enhancements would be larger if it were not for demagnetization effects that are arise because of the small lateral size of the flux concentrators.

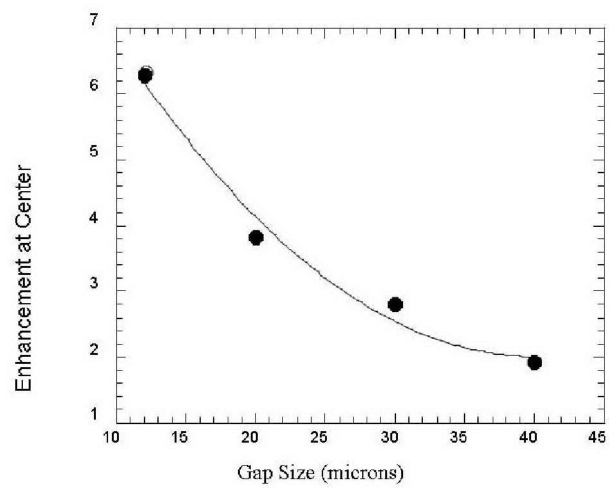
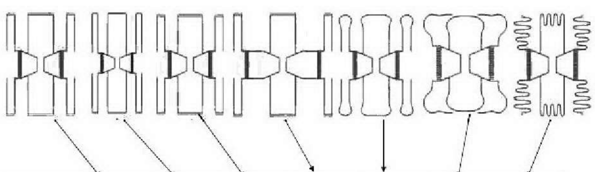


Figure 4. Modeling results for the enhancement of the magnetic field at the position of the sensor as a function of the separation of the nearest edges of the flux concentrators.

3.3 MEMS Structure

Several designs of the MEMS structure were considered. In the first design, the MEMS flaps were on torsion structures and the motion was to be driven electrostatically. It was soon decided that this design was unsatisfactory because it would be difficult to obtain a displacement large enough to provide a sufficiently large modulation of the magnetic field and because the device would be difficult to fabricate. In the subsequent designs, the motion was driven by electrostatic comb drives [8]. The thickness of the spring and separation of the teeth in the comb drive is only 2 μm. This design provides large displacements and has the further advantage that the force is independent of the displacement. The finite element program ANSYS was used to do the mechanical modeling. Figure

5 shows the seven different structures that were considered and the predicted normal mode frequencies. There are two MEMS flaps separated by 45 μm each on each side of the sensor with a flux concentrator on each flap. In each design, the MEMS flaps on each side of the sensor are connected by a MEMS spring so that their motions are correlated. If this spring were omitted, it would by very difficult to maintain the correct phase relationship between the motion of the two MEMS flaps. Because of the spring, there are two basic in-plane normal modes. One in which their motion is in phase and the other in which they are 180 degrees out of phase. The latter occurs at a higher frequency because for this mode the connecting spring must be compressed. Thus, the higher of the two frequencies for each design is for the desired 180 degree phase difference normal mode used to modulate the magnetic field.



Freq. Mode Hz ↑↑	21278	4623	8570	6123	7885	5727	8560
Freq. Mode ↑↓ Hz	38647	8198	14871	10292	12011	7886	9371
Force for 10 μ disp. μN	135.8	6.0	19.3	19.3	12.5	5.14	7.73

Figure 5. In phase and out of phase normal mode frequencies and the force required to get a 10 m displacement for several designs.

3.4 Processing Electronics

A constant current is sent through the spin valve magnetic sensor and the resulting voltage is sent to the signal processing electronics. This signal is modulated by the motion of the MEMS flux concentrator. A voltage at a frequency f_o is applied to drive the motion of the MEMS flux concentrator. This voltage, independent of its sign, creates a force that tends to increase the overlap of the teeth of the comb drive. Because the force is independent of the sign of the applied voltage, the MEMS motion occurs at a frequency $2f_o$. Thus, the signal is insensitive to pickup at the drive frequency f_o since pickup at the drive frequency can be filtered out. The original low frequency signal appears as sidebands around $2f_o$. The voltage across the spin valve first passes through a high pass filter that removes the large DC bias and then it is amplified by a broadband amplifier, demodulated and recorded.

4. FABRICATION

In early fabrications runs the MEMS structure was constructed on Si wafers. Later fabrication runs used silicon on insulator, SOI, wafers because many fewer fabrication steps are needed and because the surface on which the sensor is fabricated is smoother. The smoother surface will, in general, increase the performance of sensors. We found that most SOI wafers were not suitable. The bonding of the two silicon layers to the intervening SiO2 in most SOI wafers is poor. The poor bonding led to very anisotropic release of the MEMS structure. The HF used in the release traveled quickly through the regions of weak bonding, including the anchors that support the MEMS structure, and released all of the MEMS structure from the handle wafer, the bottom Si. This resulted in the MEMS structure floating on the surface of the liquid used to perform the release. We ordered SOI wafers from SEH America to obtain wafers with good bonding and low resistivity. The gold contacts were sputtered because contacts made by evaporation did not always provide good contact to the silicon. This occurred because the substrate was not clean enough. The MEMS structure was formed in the device layer by using deep reactive ion etching (DRIE). The silicon in the handle silicon layer below the MEMS flux concentrators was removed by DRIE to eliminate the possibility of the MEMS flux concentrators flaps contacting these surfaces. If the silicon is not removed, any voltage difference between the flaps and the silicon will tend pull the flap toward the silicon. If the MEMS flaps contact the silicon they are likely to remain permanently in contact because of stiction. If MEMS flaps and the silicon are not at the same potential, there will be an electrostatic force pulling the MEMS flaps toward silicon. Figure 6 shows a scanning electron image of the MEMS flux concentrator.

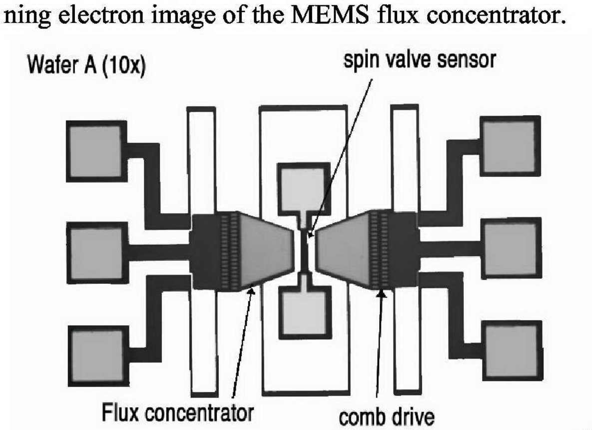


Figure 6. Scanning electron microscope image of the MEMS flux concentrator.

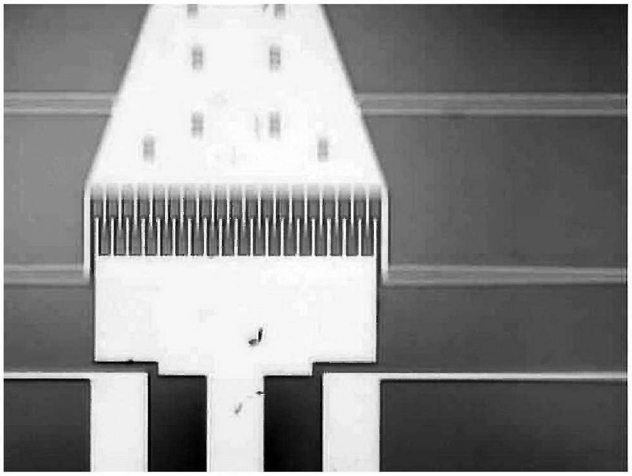


Figure 7. Optical microscope image of the motion of the MEMS flaps driven at a normal mode resonance frequency.

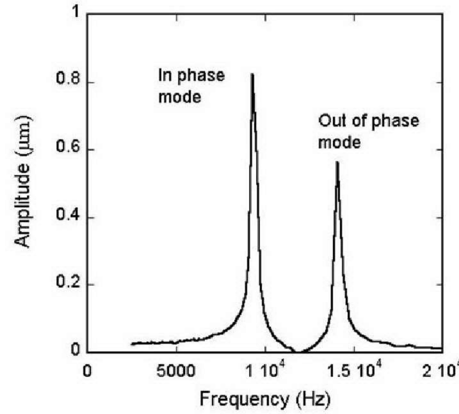


Figure 8. Plot of the amplitude of the motion at a fixed drive voltage vs. frequency, showing the two in-plane normal modes.

5. RESULTS

Figure 7 shows a microscope image of one the devices being driven at the resonant frequency. It took about 50 V to drive the motion with the amplitude shown in the figure. The portion of the image that appears out of focus has that appearance because it is undergoing a rapidly oscillating motion with a 10 micron amplitude. Figure 8 shows the amplitude of the motion of a device as a function of frequency. One sees the two normal modes. The peak amplitudes are not as large as they were in Fig. 7 because not as large a voltage was applied. The out of phase motion is the one needed to modulate the magnetic field at the position of the sensor. The Q of the out of phase resonance mode is about 30. Much larger Q's can be obtained and the device can be driven at lower voltages if the device is vacuum packaged. Figure 9 shows the magnetoresistance of one of the devices as a function of magnetic field. To obtain these characteristics for the device it was necessary first to apply a field of 135 Oe to minimize the resistivity of the spin valve. The zero field resistance of the device was 392 ohms. The data was taken by varying the magnetic field and reading the spin valve voltage as a constant current was passed through the spin valve. The magnetic field was applied using a set of Helmholz coils and a power supply operating in the constant current mode.

One sees the largest magnetoresistance change is only about 5%. To observe a field change of 1 nT at low fields, one would have to detect a voltage change of 6×10^{-8} V in a voltage of background of 0.82 Volts. This illustrates the problem of the large DC bias mentioned earlier. An important benefit of using the MEMS flux concentrator is that it modulates the field to be sensed. Thus, it eliminates the problem of the DC bias. One can use magnetic sensor systems containing a single sensor element per field direction.

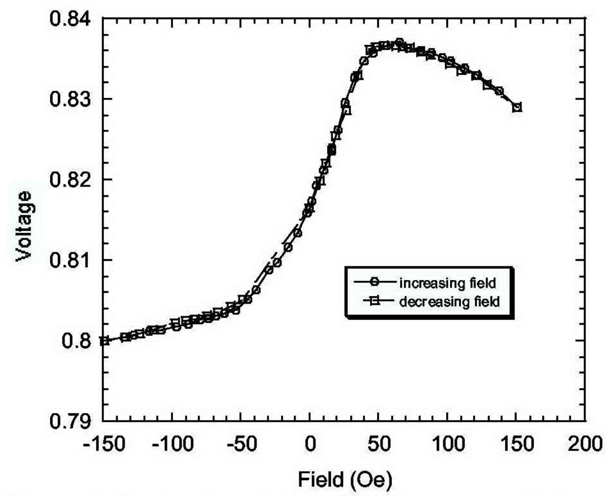


Figure 9. Resistivity of the spin valve vs. applied magnetic field.

6. CONCLUSION

Because the sensor and the MEMS flux concentrators are fabricated on the same wafer, these sensors can be mass produced at low cost. Using a single sense element per field direction, eliminates the need for sensor bridges and reduces the cost and power consumption. At the present time, we are in the process of completing a fabrication of a set of complete devices. This device should improve the low frequency performance of several types of magnetoresistance sensors by a factor of 10 to 1000. How large of an improvement can be expected depends on the magnitude of their *1/f* noise. For most types of magnetoresistance sensors, the sensors with greater sensitivity sensors also have more *1/f* noise. This correlation applies to AMR, GMR, and SDT sensors. The method works best on small sensors because one can use small

MEMS flux concentrators that are easier to drive into suitable resonance motion at high frequencies. Since the device can be fabricated by batch processing at the same time that the sensor is fabricated, it should permit the fabrication of low cost, high sensitivity magnetic sensors. The sensors should have sensitivities ranging from 10 pT to 1 nT. Another advantage of the device is that only microwatts of power are required to drive the motion.

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REFERENCES

[1] Tumanski, S., *Thin Film Magnetoresistive Sensors*. 2001, Bristol, UK: Inst. of Phys.
[2] Freitas, P.P. and *et al.*, Sensors and Actuators, 2000. Vol. A81, p. 2.
[3] Solin, S.A. *et al.*, Science, 2000. Vol. 289, p. 1530.
[4] Moodera, J.S., *et al.*, Phys. Rev. Lett., 1995. Vol. 74, p. 3273.
[5] Veedonk, R.J.M.v.d., J. Appl. Phys., 1997. Vol. 82, p. 6152.
[6] Edelstein, A.S. and G.A. Fischer, J. Appl. Phys., 2002. Vol. 91, p. 7795.
[7] Gogoi, B.P., Proceedings SPIE - International Soc. for Optical Engineering, 2004. Vol. 5344, p. 1.
[8] Trimmer, W., *Micromechanics and MEMS : classic and seminal papers to 1990*. 1997, New York: IEEE Press.

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